



Cyanobacteria dynamics in a small tropical reservoir: Understanding spatio-temporal variability and influence of environmental variables

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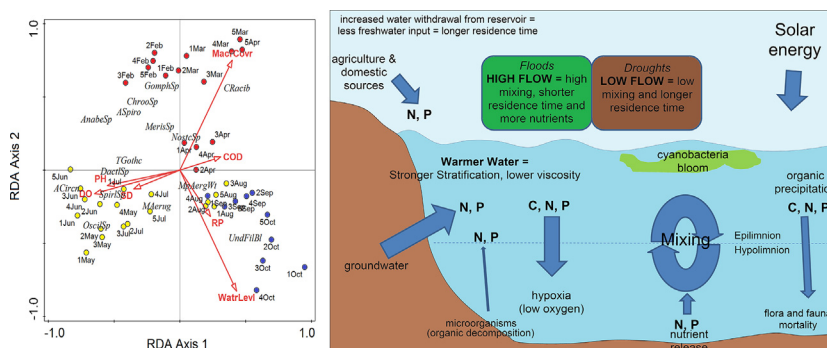
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HIGHLIGHTS

- Fifteen cyanobacteria taxa were recorded over the study period.
- *Anabaena circinalis*, *Microcystis aeruginosa* and *Chroococcus* spp. dominated.
- Cyanophyta were the more abundant taxa during the cool-dry (May and July) season.
- Using redundancy analysis, seven variables had significant effect on cyanobacteria.
- Under climate change forecasts, potentially harmful algal species may proliferate.

GRAPHICAL ABSTRACT



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ABSTRACT

Anthropogenic disturbances within or near aquatic ecosystems often contribute to eutrophication events. Cyanobacteria are a key group responsible for environmental problems associated with eutrophication processes. Interest is growing in estimating the threat of cyanobacteria in tropical Africa, however, there is still a lack of understanding regarding temporal drivers of cyanobacteria dynamics in natural aquatic ecosystems given the paucity of relevant fundamental research in this area. To better understand cyanobacteria dynamics, potential drivers of cyanobacteria dynamics were investigated in a model tropical reservoir system, whereby phytoplankton communities and water quality parameters were sampled during the tropical hot–wet, cool–dry and hot–dry seasons. Fifteen cyanobacteria taxa were recorded over the study period. *Microcystis* spp. and *Cylindrospermopsis* spp., known cyanotoxins producers, were the most prevalent bloom-forming taxa found in the study, with overall Cyanobacteria relative abundances being greatest during the cool-dry season. This was likely driven by decreased river inflows and increased reservoir mixing during the cool-dry period. Combinations of macrophyte cover, dissolved oxygen levels, water transparency, reactive phosphorus, water depth and chemical oxygen demand were found to significantly affect cyanobacteria community structure. The study highlights that under climate change forecasts (for much of tropical arid Africa), potentially harmful and problematic algal species may proliferate. Management options, therefore, need to be explored to maintain water quality and potable availability to mitigate against indirect harmful effects of environmental changes on ecosystems and human communities that utilise their services.

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1. Introduction

One of the major problems associated with anthropogenic disturbance of aquatic ecosystems is that of eutrophication. Eutrophication has many undesirable symptoms such as high phytoplankton biomass, oxygen depletion, decrease in water transparency, unpleasant taste and odour, and drinking-water treatment problems (Mhlanga et al., 2006; Chinyama et al., 2016; Mantzouki et al., 2016; Ndlela et al., 2016). Many of the problems associated with eutrophication are, however, caused by the prevalence of Cyanobacteria. Cyanobacteria are a diverse group of organisms that differ widely in their functional traits, many of which are undesirable from a water quality perspective (Brasil et al., 2016; Havens et al., 2017). In the past few decades, many of the world freshwater and marine environments have experienced a steady increase in cyanobacterial blooms due to the algae rapid multiplication as a result of eutrophication (Fastner et al., 2003; Preußel et al., 2006; Liao et al., 2016; Mantzouki et al., 2016; Ndlela et al., 2016). These cyanobacteria can produce a wide range of potent toxins which may have health implications for aquatic life, livestock and wild animals (Mhlanga et al., 2006; Baig et al., 2017; Brient et al., 2017) and even humans (Funari and Testai, 2008; Funari et al., 2017; Rezaitabar et al., 2017).

Recent studies (i.e. IPCC, 2013; Brasil et al., 2016; Walls et al., 2018) have suggested that climate change may further intensify eutrophication symptoms in parts of the world. According to the Intergovernmental Panel on Climate Change (IPCC, 2013) report, many arid and semi-arid regions are likely to become warmer and drier by the end of the current century, partly due to anthropogenic induced climate change. Cyanobacteria within the tropics may show persistent annual dominance with relatively small changes during the year and often being toxic (Duong et al., 2013). High cyanobacterial bloom densities can also create problems associated with aesthetics and odour, lower water quality, increase turbidity and disrupt energy transfer in aquatic food webs as most cyanobacteria are not palatable to primary consumers (Preußel et al., 2006; Liao et al., 2016; Havens et al., 2017).

Although cyanobacteria blooms are typically associated with nutrient enrichment, their appearance has been related to several factors, such as adaptation to low carbon dioxide concentrations, high temperature and pH levels, low light conditions, and water column stability, ability to store phosphorus, nitrogen limitation, production of allelopathic substances and resistance to herbivory (Havens et al., 2017). Phosphorus has been considered as the most important limiting nutrient in freshwater ecosystems and identified as being the main cause of eutrophication (Brasil et al., 2016). However, most investigators have advocated for the consideration of both nitrogen and phosphorus as the major causes of eutrophication and cyanobacterial blooms (Conley et al., 2009; Funari et al., 2017; Cremona et al., 2018). Hence, the concept of nutrient limitation is therefore considered key for cyanobacteria research, as it is in eutrophication research in general.

Despite the growing interest in estimating the threat of cyanobacteria in tropical Africa, there is still a lack of regular monitoring, management and even fundamental research (Ndlela et al., 2016). Therefore, the current study focussed on small tropical water-body cyanobacteria dynamics. Small water bodies are particularly interesting given their high surface area to volume ratio, and increased susceptibility pollution effects because of their small size. Given the need for potable water, small rivers are often impounded in arid regions, increasing the number of small standing water bodies at the regional landscape level. These water bodies become important for local communities that invariably come to rely on the services provided by more permanent water availability. To better understand cyanobacteria dynamics in these ecosystems, we assessed the composition and potential drivers of cyanobacteria in a small tropical reservoir used for recreational activities and water supply in the semi-arid region of Zimbabwe. The overall trends of cyanobacterial blooms were studied in relation to the variation in environmental variables in order to understand how the

communities respond to hydrodynamic and thermal stratification events with regards to changes in community structure. This study facilitates our current understanding of the diversity and ecology of cyanobacteria within small tropical reservoirs with implications for effective management of such reservoirs.

2. Materials and methods

2.1. Study area

Malilangwe Reservoir is located in the south-eastern lowveld of Zimbabwe (20°58'–21°02' S, 31°47'–32°01' E), with a mean annual rainfall of 562 mm. Approximately 84% of the rainfall occurs between November and March and the area is prone to droughts due to erratic rainfall patterns. Summer temperatures are high, with a daily maxima of >32 °C and peak temperatures of >45 °C. Winters are generally cool, with temperatures ranging from 5 °C to 26 °C (Zimbabwe Meteorological Office, 2007). Malilangwe Reservoir is mostly used as a water supply and it is a gravity section masonry dam, with a surface area of 211 ha, maximum depth is 14.3 m (mean depth 4.5 m) and a maximum volume of $12 \times 10^6 \text{ m}^3$.

The reservoir is vegetated with at least seven plant species belonging to five families (i.e. Cyperaceae (2 spp.), Poaceae (2), Onagraceae (1), Potamogetonaceae (1), Salviniaceae (1)) occurring in patches along the littoral zone (Dalu et al., 2012a) and is inhabited by eight fish species belonging to five families i.e. Cichlidae (4 spp.), Alestidae (1), Clariidae (1), Cyprinidae (1) and Gobiidae (1) being recorded (Dalu et al., 2012b). Sampling was carried out once a month at five selected sites throughout the three main seasons for the region; hot–wet (February to April), cool–dry (May to August) and hot–dry (September to October).

2.2. Environmental variables

Conductivity, dissolved oxygen (DO), pH, temperature and total dissolved solutes (TDS) were measured on-site at 1 m depth intervals using a multiparameter meter (HACH, LDO, Germany). Water transparency and level were measured using a Secchi disk and tape measure with an anchor, respectively. Integrated water samples were further collected using a Ruttner water sampler (KC Denmark) at each site at 1 m depth intervals for nutrients and chemical oxygen demand (COD) analysis in the laboratory (Dalu et al., 2013a). The COD was determined using the closed-reflux digestion method (EPA method 410.4; HACH method 8000; Standard Methods 5520D), with a precision of $\pm 2.7 \text{ mg L}^{-1}$. Nutrients i.e. total nitrogen (TN) were determined using the persulphate digestion method (HACH method 10,071) at a precision level of $<1 \text{ mg L}^{-1}$, ammonium using the salicylate method (HACH method 10,023) at a precision level of $\pm 0.03 \text{ mg L}^{-1}$, reactive phosphorus using the PhosVer 3 method (HACH method 8048; USEPA method 365.2; Standard Methods 4500 P-E) at a precision of $\pm 0.02 \text{ mg L}^{-1}$ and total phosphorus was determined using the PhosVer 3 with acid persulphate digestion method (HACH method 8190; Standard Methods 4500 P-E), at an estimated detection limit of 0.04 mg L^{-1} .

2.3. Phytoplankton sampling

Phytoplankton samples for determination of cyanobacteria were collected using vertical hauls with a phytoplankton net (20 μm mesh size, 40 cm diameter) at a speed of $\sim 0.6 \text{ m s}^{-1}$. The concentrated samples were collected in 250 mL bottles and preserved in Lugol's iodine solution. The cyanobacteria samples were identified and scored under an inverted microscope (Olympus CKX41) using the Utermöhl's sedimentation method (Utermöhl, 1958) with the density of cyanobacteria being determined by counting the numbers present in five 10 mL subsamples from each site (~ 60 – 100 cells of the dominant species; Mhlanga et al., 2006) and with the mean value being recorded. All

counting was done under 400× magnification using differential interference-contrast optics. The cyanobacteria were identified to the lowest taxonomic level using keys by Cander-Lund and Lund (1995) and John et al. (2002).

2.4. Data analysis

The species richness, evenness, dominance and Margalef, Shannon–Weiner and Simpson's diversity indices were calculated using the cyanobacteria relative abundance dataset in PAST version 3.0 (Hammer et al., 2001). Distance-based permutational analysis of variance (PERMANOVA; Anderson, 2001) were used to analyse whether cyanobacteria abundance and environmental variables differed between sites and seasons (hot–wet, cool–dry, hot–dry) using PERMANOVA+ for PRIMER version 6 (Anderson et al., 2008). Bray Curtis and Euclidean distance dissimilarities were employed for biological and environmental data, respectively at 9999 permutations.

For all community analysis, all cyanobacteria species data were square-root transformed to reduce skewness, whereas, all environmental variables data with exception of pH were $\log(x + 1)$ transformed. To determine whether to use linear or unimodal methods, a Detrended Canonical Correspondence Analysis (DCCA) was used. The lengths of gradient were examined and since the longest gradient was <3.0, a linear constrained method i.e. Redundancy Analysis (RDA) was selected. An RDA analysis was performed on the transformed cyanobacteria relative abundance dataset to examine the links between cyanobacteria species composition and environmental variables. Stepwise manual forward selection was then employed to identify a minimal subset of environmental variables that were significantly related to the cyanobacteria community structure (Monte Carlo test with 9999 permutations). The software Canoco (ver. 5) was used for the analysis (Ter Braak and Šmilauer, 2012).

A non-parametric multi response permutation procedure (MRPP) was used to test for differences among three seasons. When heterogeneity within groups equals expectation by chance, then $A = 0$ (i.e. the highest possible value for A), and when all items are identical within groups, then the observed delta = 0 and $A = 1$, and if there is less agreement within groups than expected by chance, then $A < 0$. The MRPP was based on Sorensen (Bray–Curtis) as a distance measure, the groups weighting: $n/\text{sum}(n)$ (Mielke et al., 1976) was calculated in PC-ORD version 5.10 (McCune and Mefford, 2006).

The indicator species analysis (IndVal; Dufrêne and Legendre, 1997) was used to identify indicator species within the communities during the different sampling seasons based on all 15 identified cyanobacteria taxa (Dufrêne and Legendre, 1997). The indicator values range from zero (no indication) to 100 (perfect indication). The species with significant indicator values ($p < 0.05$) were considered as good indicator species. The IndVal analysis was carried out using Monte Carlo test with 9999 permutations in PC-ORD version 5.10 (McCune and Mefford, 2006).

3. Results

3.1. Environmental variables

Environmental variables highlighted strong seasonal variation (ANOVA, $p < 0.01$), with dissolved oxygen (DO), total nitrogen (TN), ammonium and Secchi disk depth i.e. water transparency showing strong site variation (ANOVA, $p < 0.01$). Temperature, conductivity, total dissolved solids (TDS), TN, ammonium, chemical oxygen demand (COD) and total phosphorus showed significant water depth variation (ANOVA, $p < 0.01$). The measured environmental variables are presented in Figs. 1 and 2 and Table S1. Thermal stratification was established during the hot-wet season, with mean water temperatures at the water surface being about 31.2 °C (Fig. 1). The reservoir was not stratified during the cool- and hot-dry seasons and was completely

mixed. The reactive and total phosphorus was generally high at the bottom (<8 m depth) during the hot-wet season, while the opposite was observed for the hot-dry season when the bottom waters were low in phosphorus concentrations but the surface waters had high concentrations (Fig. 2a, b). Ammonium and total nitrogen was high in the bottom waters during the hot-wet season (Fig. 2c, d). During the cool-dry season i.e. reservoir mixing, the nutrient concentrations were generally low (Fig. 2).

3.2. Cyanobacteria community structure

A total of 15 cyanobacteria taxa belonging to 9 families were recorded from Malilangwe reservoir over three study seasons (Table 1). *Cylindrospermopsis raciborskii* (Woloszynska) Seenayya and Subbaraju (30.7%), unidentified filamentous cyanobacteria (13.9%), *Merismopedia* sp. (12.8%) and *Chroococcus* sp. (abundance 10.4%) were the most abundant taxa during the hot-wet season when the reservoir was well stratified, whereas in the cool-dry season the reservoir was weakly stratified (well mixed) and cyanobacteria blooms were observed. Three species dominated (>70% abundance): *Anabaena circinalis* Rabenhorst ex Bornet and Flahault – 33.9%, *Microcystis aeruginosa* (Kützinger) Kützinger – 21.3%, *Chroococcus* sp. – 17.5% (Table 1). Cyanobacteria total abundances were found to differ significantly among sites (PERMANOVA; Pseudo- $F_{(1,43)} = 4.216$, $p < 0.001$) and seasons (PERMANOVA; Pseudo- $F_{(1,43)} = 2.296$, $p = 0.019$).

Cyanobacteria taxa richness ranged between 4 and 11 (mean 7.2) in the hot-wet season and between 2 and 11 (mean 6.5) in the cool-dry season, and decreased to 3–7 (mean 4.7) during the hot-wet season (Table 1). Taxa richness ($F_{(2,42)} = 3.840$, $p = 0.033$), evenness ($F_{(2,42)} = 3.491$, $p = 0.044$), Shannon–Weiner index ($F_{(2,42)} = 3.653$, $p = 0.038$) and Margalef index ($F_{(2,42)} = 3.825$, $p = 0.034$) differed among seasons but similarities were observed across the study sites. The diversity indices were high during the hot-wet season, with the hot-dry season having a lower cyanobacteria diversity (Table 1).

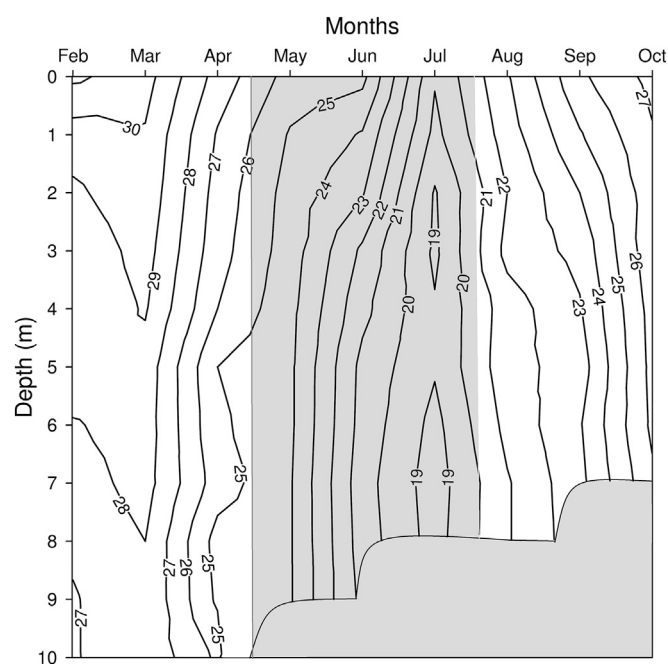


Fig. 1. Variation in water temperature (°C) with depth (m) at the index site (deepest point near the dam wall) of the Malilangwe Reservoir between February and October 2011. The grey area represents time when algal blooms were observed and the units for numbers are °C and grey area bottom right indicate changes in water depth with time.

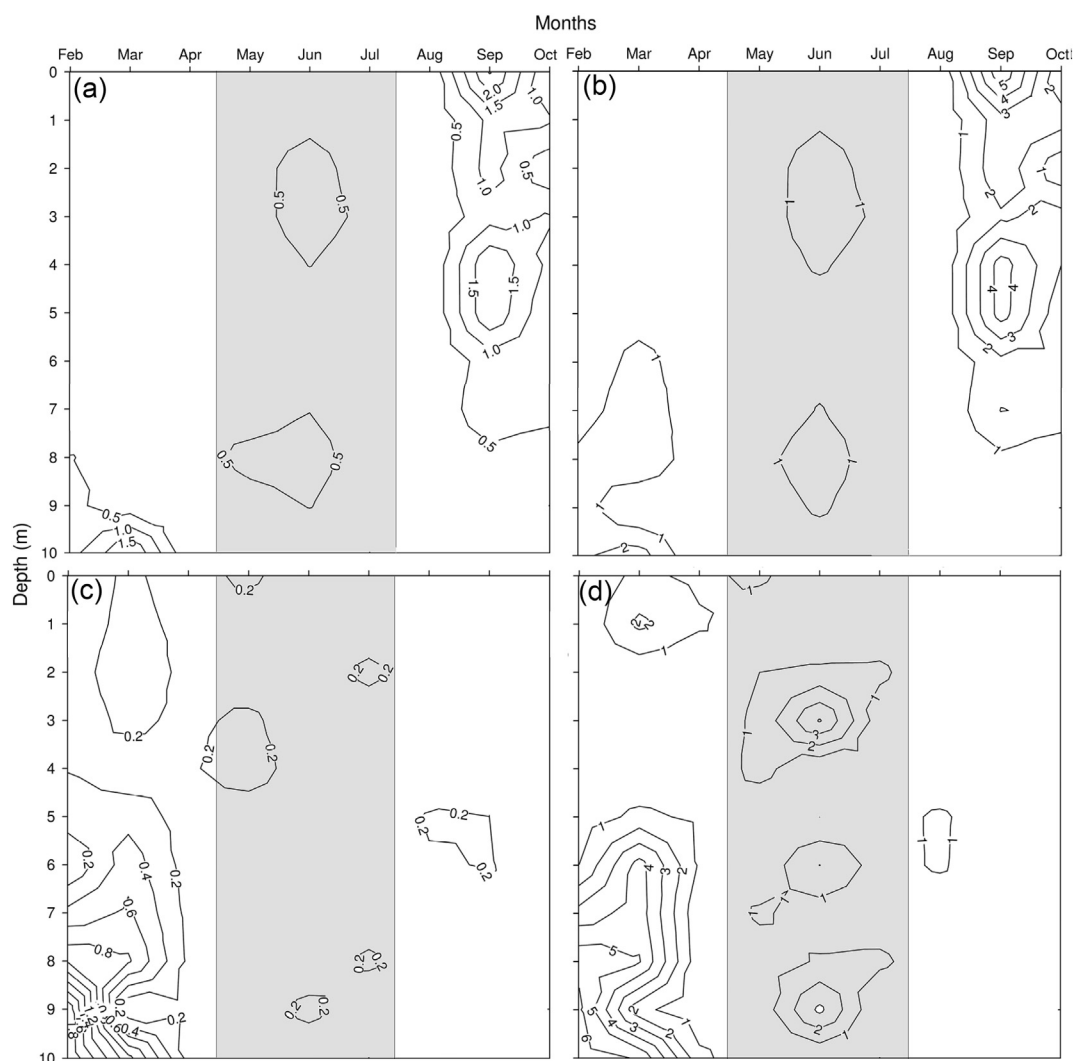


Fig. 2. Variation in (a) reactive phosphorus, (b) total phosphorus, (c) ammonium and (d) total nitrogen measured from the index (i.e. deepest) site. The grey area represents time when algal blooms were observed and the numbers are concentrations in mg L^{-1} .

Table 1
Mean relative abundances (%) of the cyanobacteria taxa and community metrics (mean \pm standard deviation) observed over three study seasons. Values were calculated from all sites for each season.

| Taxa | Family | Toxin producing ^a | Hot-wet | Cool-dry | Hot-dry |
|--|--------------------|------------------------------|---------------|---------------|----------------|
| <i>Anabaena circinalis</i> Rabenhorst ex Bornet and Flahault | Nostocaceae | × | 2.1 | 33.9 | |
| <i>Anabaena</i> sp. | Nostocaceae | × | 6.1 | 8.3 | 4 |
| <i>Anabaena spiroides</i> Klebahn | Nostocaceae | × | 3.5 | 2.5 | |
| <i>Chroococcus</i> sp. | Chroococcaceae | | 10.4 | 17.5 | |
| <i>Cylindrospermopsis raciborskii</i> (Woloszynska) Seenayya and Subbaraju | Nostocaceae | × | 30.7 | 0.8 | 35.7 |
| <i>Dactylococcopsis</i> sp. | Chroococcaceae | | 2.5 | 1.1 | 1.6 |
| <i>Gomphosphaeria</i> sp. | Gomphosphaeriaceae | | 3 | | |
| <i>Merismopedia</i> sp. | Merismopediaceae | | 12.8 | 2 | 6 |
| <i>Microcystis aeruginosa</i> (Kützinger) Kützinger | Microcystaceae | × | 8.1 | 21.3 | 34 |
| <i>Pseudanabaena mucicola</i> (Naumann and Huber-Pestalozzi) Schwabe | Pseudanabaenaceae | | 1.3 | 1.8 | |
| <i>Nostoc</i> sp. | Nostocaceae | | 1.8 | | |
| <i>Oscillatoria</i> sp. | Oscillatoriaceae | × | | 1.6 | 0.2 |
| <i>Spirulina</i> sp. | Spirulinaceae | | 3.9 | 6.5 | 0.2 |
| <i>Tetrapedia gothica</i> Reinsch | Hydrodictyaceae | | 0.1 | 0.1 | |
| Unidentified filamentous cyanobacteria | | | 13.9 | 2.4 | 18.2 |
| Taxa richness | | | 7.2 \pm 1.9 | 6.5 \pm 2.5 | 4.7 \pm 1.2 |
| Dominance | | | 0.2 \pm 0.1 | 0.3 \pm 0.3 | 0.4 \pm 0.1 |
| Evenness | | | 1.2 \pm 0.1 | 1.1 \pm 0.1 | 1.1 \pm 0.04 |
| Shannon Index | | | 2.1 \pm 0.3 | 1.9 \pm 0.6 | 1.6 \pm 0.3 |
| Simpson Index | | | 0.8 \pm 0.1 | 0.7 \pm 0.3 | 0.7 \pm 0.1 |
| Margalef Index | | | 2.2 \pm 0.5 | 2.0 \pm 0.6 | 1.6 \pm 0.3 |

^a Potential toxin producing taxa were identified based on HARNNESS (2005).

3.3. Relationship between cyanobacteria and environmental variables

Based on RDAs carried out for individual variables, seven variables (i.e. macrophyte cover, DO, water transparency, reactive phosphorus, water level depth, COD) were found to have a significant effect on cyanobacteria community structure (Fig. 3; Monte Carlo permutation test, $p < 0.050$). The first four RDA axes accounted for 48.2% of the fitted variation, with the RDA axes 1 and 2 accounting for 32.9% (axis 1 (22.9%) and 2 (10%)) variation in cyanobacteria composition. Hot-wet season sites (February to April) were positively associated with RDA axis 2 and were characterised by high macrophytes cover and COD, and lower water level and transparency, pH, reactive phosphorous concentration and DO. Examples of cyanobacteria that were associated with these sites included *Nostoc* sp., *Anabaena spiroides* Klebahn, *Anabaena* sp., *Gomphosphaeria* sp. and *C. raciborskii* (Woloszynska) Seenayya and Subbaraju (Fig. 3). Cool-dry (May to August) and hot-dry (September to October) season sites were negatively associated with RDA axis 2, being characterised by higher DO, water level and transparency, pH and reactive phosphorous concentration. Examples of cyanobacteria that were associated with these sites included *A. circinalis* Rabenhorst ex Bornet and Flahault, *Spirulina* sp., *M. aeruginosa* (Kützing) Kützing, *Pseudanabaena mucicola* (Naumann and Huber-Pestalozzi) Schwabe and *Oscillatoria* sp. (Fig. 3).

Based on significant indicator values ($p < 0.05$), nine significant indicator species were identified from the three different sampling seasons: *A. circinalis* (cool-dry, IndVal = 40.2%), *Oscillatoria* sp. (cool-dry, IndVal = 35.2%), *Spirulina* sp. (cool-dry, IndVal = 37.8%), *A. spiroides* (hot-wet, IndVal = 46.2%), *Chroococcus* sp. (hot-wet, IndVal = 44.4%), *C. raciborskii* (hot-wet, IndVal = 45.8%), *Gomphosphaeria* sp. (hot-wet, IndVal = 40%), *Merismopedia* sp. (hot-wet, IndVal = 35.4%) and

unidentified filamentous cyanobacteria (hot-dry, IndVal = 52.8%). Using MRPP analysis, statistically significant differences was identified in cyanobacteria communities between study periods (observed delta = 0.407, $A = 0.195$, $p < 0.001$), with significant differences being observed for all seasons: hot-wet vs cool-dry ($A = 0.094$, $p < 0.001$), hot-wet vs hot-dry ($A = 0.240$, $p < 0.001$) and hot-dry vs cool-dry ($A = 0.173$, $p < 0.001$). The group and/or cluster differences were strongly associated with differences in environmental variables within the study periods.

4. Discussion

Existing nutrient enrichment of aquatic ecosystems, along with projected climate shifts, will likely have implications for the prevalence and persistence of many harmful algal species (IPCC, 2013; Brasil et al., 2016; Walls et al., 2018). Understanding the drivers of potentially problematic species is key for the mitigation of effects associated with their increased prevalence. Using a model small reservoir, the present study highlights that certain conditions are conducive for key Cyanobacteria proliferation in semi-arid sub-tropical environments. In the present study, Cyanobacteria were present in all three seasons. Cyanobacteria were, however, the more abundant taxa during the cool-dry (May and July) season and this change in species composition followed an increase in phosphorus in May which likely drove the increase in nitrogen-fixing species such as *A. circinalis*, *Chroococcus* sp. and *M. aeruginosa* (Table 1). The high cyanobacteria densities observed during the cool-dry season could also have been, at least partially, attributed to the decrease in the destabilising effects of river inflows and increased reservoir mixing (Dalu et al., 2013b). Hence, the cyanobacteria bloom observed during the complete water mixing period (i.e. turnover) was probably related to an even distribution of nutrients and other environmental variables throughout the water column (Fig. 2). These resuspended nutrients now in the epilimnion were best exploited by cyanobacteria with intracellular nutrient (i.e. nitrogen, phosphorus) storage capacities.

Overall, the high pH, low nitrate and nitrogen concentration and low water transparency in the reservoir were associated with increased cyanobacteria abundance in the present study. Asiyo (2003) showed similar results, whereby it was observed that cyanobacteria proliferated when nitrogen/nitrate concentrations were low. It has been shown that many cyanobacteria have a high affinity for absorbing nutrients at very low concentrations (i.e. some are nitrogen fixing) and have the ability to capture light at low light situations (Asiyo, 2003; Paerl and Paul, 2012). Thus, cyanobacteria are at an advantage under low light and nutrient conditions, which enable them to survive and proliferate when other phytoplankton species are unable to (Olguín et al., 2001; Cremona et al., 2018) and some of these species may present useful signals for environmental conditions, based on indicator species test results. Seasonal indicator cyanobacteria species were also identified, with five species identified for the hot-wet period, three for cool-dry period, and only one in the hot-dry period.

Thermal stratification is an important natural phenomenon in aquatic ecosystems, which interferes significantly with the water physical and chemical structure, creating complex gradients, leading to increased water column heterogeneity (Gao et al., 2016; Richardson et al., 2017). Warming of surface waters intensifies vertical stratification and seasonal warming also lengthens the period of stratification. In Malilangwe reservoir, stratification tends to take place towards the end of hot-dry season and the stratification is maintained throughout the hot-wet season, while destratification occurs throughout cool-dry season (Dalu et al., 2013c). Many cyanobacteria species e.g. *C. raciborskii*, *Chroococcus* sp. and *Merismopedia* sp. were able to uniquely exploit stratified conditions. Most bloom-forming cyanobacteria such *M. aeruginosa* and *Anabaena* spp. contain gas vesicles which provide buoyancy (Paerl and Paul, 2012), enabling them to form dense surface blooms during the destratified waters period (Fig. 1), where they

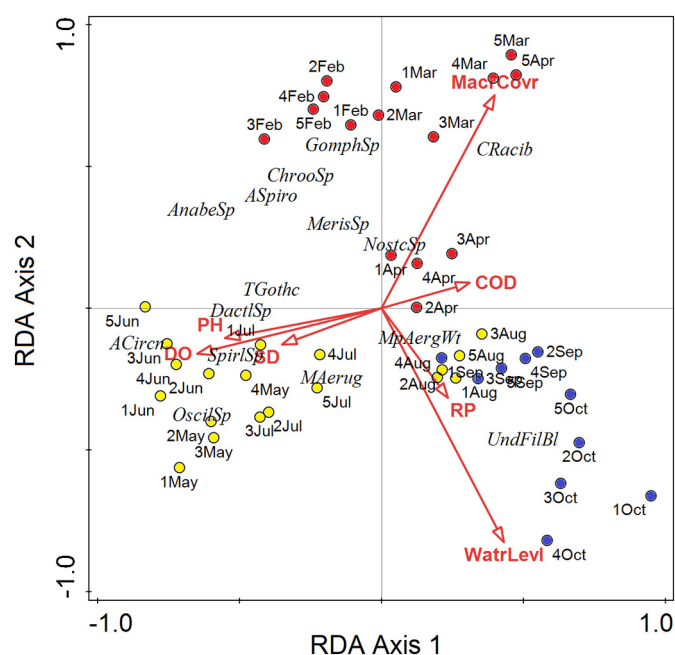


Fig. 3. Redundancy analysis plot highlighting cyanobacteria communities and taxa in relation to selected significant ($p < 0.05$) environmental variables. Abbreviations: MacCovr – macrophyte cover, DO – dissolved oxygen, SD – Secchi disk depth (i.e. water transparency), RP – reactive phosphorus, WaterLevl – water level depth, COD – chemical oxygen demand; numbers next to months are sites, red – hot-wet season, yellow – cool-dry season, blue – hot-dry season, and species: ACircn – *Anabaena circinalis*, AnabaSp. – *Anabaena* sp., ASpiro – *Anabaena spiroides*, ChrooSp. – *Chroococcus* sp., CRacib – *Cylindrospermopsis raciborskii*, DactlSp. – *Dactylococcopsis* sp., GompSp. – *Gomphosphaeria* sp., MerisSp. – *Merismopedia* sp., MAerug – *Microcystis aeruginosa*, NostcSp. – *Nostoc* sp., OscilSp. – *Oscillatoria* sp., MpaAerWt – *Pseudanabaena mucicola*, SpirSp. – *Spirulina* sp., TGothe – *Tetrapedia gothica*, UndFilBl – Unidentified filamentous cyanobacteria.

utilised the added advantage of high temperatures (i.e. surface water temperature ranged between 19 °C (night) and 28 °C (day) (Dalu et al., 2013c)) to optimize photosynthesis. Under the effects of climate change many of the physical characteristics of aquatic ecosystems may also change favouring the cyanobacteria dominance. For example, an increase in thermal stratification and the consequent reduction of the vertical turbulent mixing and the widening of the stratification period will strengthen and extend the period of optimal growth of many cyanobacterial species such as *C. raciborskii*, *Chroococcus* spp. and *Merismopedia* spp. In stratified ecosystems, less nutrients are available at the surface and since cyanobacteria are able to regulate their buoyancy, they will obtain nutrients from deeper layers of water and the atmosphere (Dantas et al., 2011; Flores et al., 2015; Molot, 2017).

The regular mixing of the water column has likely influenced the plankton distribution within the tropical reservoir, as has been shown from both similar climatic regions, and more temperate systems (Berger et al., 2007; Amaral et al., 2018). Similar observations were made for Jebel Apulia Reservoir (Sudan) and Pilkington Bay, Lake Victoria (Uganda) (Talling, 1957), where the distribution of photosynthetic cyanobacteria and photosynthetic activity was influenced by regular water mixing. Diurnal stratification cycles induced regular fluctuations of nutrient concentrations in Eleiyele Reservoir (Nigeria), having a direct influence on plankton numbers (Imevbore, 1967). Dupuis and Hann (2009) reported that warm springs and summers associated with thermal stratification in the Fort Whyte Lakes (Canada) were correlated with increased total phytoplankton and relative cyanobacteria biomass, being consistent with long-term patterns observed in several North American and European lakes in which thermal stratification had been linked to phytoplankton blooms and increased total biomass.

In the present study, Cyanobacteria species were found throughout the year. However, the period associated with the most risk was the cool-dry season as Cyanobacteria were most abundant taxa during this time of the year. The known cyanotoxin producers, *Anabaena*, *Microcystis* and *Cylindrospermopsis*, were among the most prevalent bloom-forming taxa found in the present study. Their frequent occurrence suggests a high risk of potential exposure to toxigenic cyanobacteria and associated cyanotoxins to animals and humans through recreational activities and drinking. This would have serious socio-economic costs for humans, using this reservoir (or living in this area). The study did not, however, assess Cyanotoxin production in the system. Regional context is important in cyanotoxin studies, given that the many toxin producing algal species only do so under certain conditions. Future studies should, therefore, investigate in situ cyanotoxin levels associated with the numerical responses of key Cyanobacteria species. Such an approach will help highlight the most important regional indicator Cyanobacteria species that should be prioritised for monitoring.

Management around mitigating effects of harmful water quality for users is complicated. This is further complicated by changing environmental conditions, as management options often need to be changed accordingly. Studies such as these can, however, inform management options through the identification of high-risk scenarios. The study highlights that under certain environmental conditions, potentially harmful cyanobacterial species proliferate. Reactive phosphate levels, for example, was identified as an important driver of Cyanobacteria numbers and was associated with low water levels. Such identification of drivers and periods of risk will aid in the establishment of risk mitigation protocols, such as when to intensify monitoring activity, when to restrict access to reservoirs or when to assist local communities with ex situ potable water purification. Within the context of shifting climates, this is of great relevance, given that climate change forecasts suggest that environmental conditions may become more favourable for many problematic species.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.scitotenv.2018.06.256>.

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